Formulation of Available Energy-Based Methods to Assess System Affordability

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Abstract: This paper describes the fundamental motivation and ideas surrounding current developments in available energy-based methods for vehicle design, which are a class of methods allowing direct estimation of the *total cost* chargeable to each loss mechanism in any general vehicle design (land, sea, air, or space). It is shown that losses can be expressed in terms of chargeable fuel weight. These are in turn expressed in terms of cost breakdowns. The method is demonstrated for a notional Boeing 737/CFM56 example for which fuel chargeability is determined based on the various loss mechanisms inherent to the engine/airframe. This technique is then used to derive a detailed breakdown of direct operating cost, and the potential of this technique for evaluation of the impact due to environmental technologies, including uncertainties, is discussed.

Introduction: The performance of modern transportation systems today is measured in terms of environmental impact, engine internal thermodynamic performance (fuel consumption), subsystem weight, and above all, cost. One of the fundamental activities of the design process is finding a balance between these competing design requirements, which is usually done through a series of trade studies. Today's analytical methods allow very accurate estimates of vehicle performance, sized vehicle weight, and total operating costs. However, the impetus today is to quantify all the above performance metrics in terms of cost. In particular, it is of interest to know the absolute contribution of each individual loss to total operating cost (and uncertainty thereof), a capability that does not currently exist. Moreover, the number of metrics that are important to design performance continues to grow as time passes, resulting in additional complication to the task of identifying the best design.

Available Energy Methods in Design: One class of techniques that is now becoming available as a means of solving these problems are loss management models.[1] These are analytical models that combine recent developments in thermodynamics and exergy methods[2] with classical design and weight management methods to enable the calculation of the *absolute cost* associated with each loss mechanism relevant to the operation of the vehicle.[3,4] The fundamental idea behind loss management models is the realization that *all losses in a vehicle system can be expressed in terms of chargeable fuel weight.* The advantage of this approach is that all traditional sub-system performance metrics are expressed in terms of equivalent chargeable fuel weight and are therefore *directly comparable* to each other.

Table I: Assumed Engine Component Efficiencies for a Notional CFM56-3C-1 Turbofan Engine.

Assumed Cycle:	*Component Efficiencies*
Turbine Inlet Temp.=2800R	Fan/Booster Efficiency = 0.92
Overall Press. Ratio = 28.8	Low Turbine Efficiency = 0.91
Bypass Ratio = 5	High Compressor Eff. = 0.88
Fan Pressure Ratio = 1.7	High Turbine Efficiency = 0.91
	No Chargeable Cooling

For instance, the design of a modern jet engine is fundamentally a balance between engine internal losses (usually expressed as specific fuel consumption), nacelle drag, and engine weight. Loss management models allow engine internal performance and nacelle drag to be expressed in terms of fuel burn increments chargeable to these losses. Thus, nacelle drag and engine internal losses are directly comparable to engine weight in terms of their contribution to overall aircraft weight. Moreover, it is relatively simple to translate the chargeable fuel weights into operating costs. Consequently, one can easily calculate the total cost due to any functional group or individual loss mechanism.

Application to Boeing 737/CFM56: The basic theory underlying the development of loss management models is best explained through a discussion of typical results obtainable using this method. Consider a notional Boeing 737-300 transport powered by CFM56-3C-1 engines at maximum power M0.8, 35,000 ft cruising flight (the takeoff, climb, and descent phases are ignored in the interest of simplicity).[*] The first step in application of loss management methods to this engine/airframe is to calculate the loss breakdown due to inefficiencies within the engine itself. This can be done a variety of ways, but for simplicity's sake, the available energy method[5] is used here as a first approximation. Based on the assumed engine component efficiencies given in Table I, the available energy breakdown can be calculated as shown in the left side of Figure 1. Note that losses internal to the engine constitute roughly 15% of the total available energy produced by the core, with the other 85% effectively going towards the production of useful thrust work. This available energy breakdown can be directly translated into fuel flow chargeability, as shown on the right side of Figure 1. This shows that 15% of the total fuel flow being used by the engines is directly chargeable to internal losses in the engines, with the remainder being used to do drag work on the atmosphere.

The next step in the development of this B737 loss management model is to further subdivide the drag fuel flow chargeability according to the cruise drag

[*] This example uses manufacturer's published data where publicly available, and assumes approximate data for those cases where data is not publicly available.

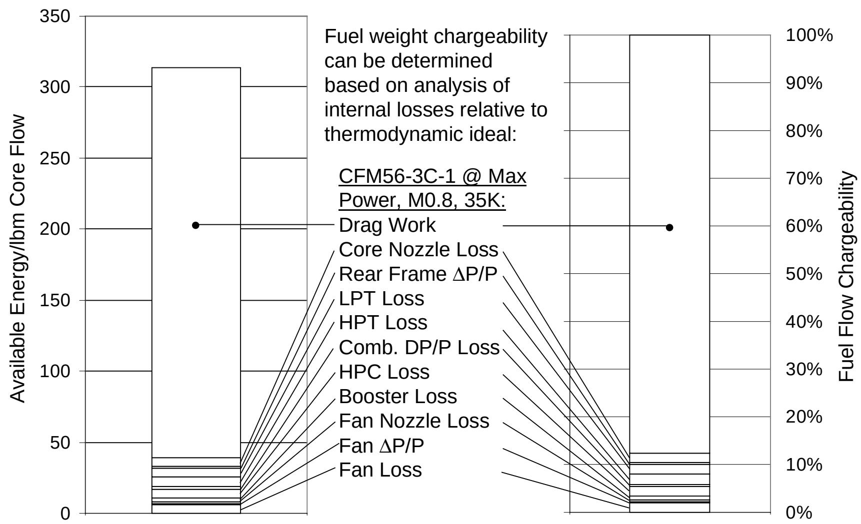

Figure 1: Fuel Weight Chargeability for Notional CFM56-3C-1 at Maximum Power Cruise Flight Conditions.

Table II: B737-300 Weight Breakdown (From Company Literature).

Weight Group	*Weight*
Gross Weight	124,500 lb
Empty Weight	72,360 lb
Fuel	35,053 lb
Cargo/Passengers	17,087 lb
Engine	4,301 lb (ea)

breakdown of the vehicle. The assumed drag breakdown for the B737 in cruising flight is given in Figure 2. Note that roughly 25% of the drag is due to lift (induced drag), and a further 22% of the drag is due to wing skin friction. One could argue that since the function of the wing is to lift the weight of the vehicle, wing drag (along with its fuel flow chargeability) is due to the weight of the vehicle. Therefore, wing fuel flow chargeability can be further subdivided in proportion to the weight breakdown of the aircraft given in Table II.

If these various chargeable components of fuel flow are integrated through the mission, the result is the total fuel weight chargeable to each source of loss. The results of this simplified analysis for the B737-300 are given in Figure 3, which shows a breakdown of total fuel weight according to the contribution made by each functional component. Note that the largest single contributors to vehicle fuel weight are airframe & systems weight and fuselage drag. Engine internal losses account for roughly 14% of total fuel weight, nacelle drag another ~8%, and engine weight a further ~4%. Thus, the total propulsion system contribution to vehicle fuel weight is 26%.

Given this breakdown in fuel weight chargeability, it is relatively straightforward to translate this into detailed breakdowns of direct operating costs (DOC). This idea is shown in Figure 4, which gives a typical direct operating cost breakdown for a 737-300 aircraft on the far left. The fuel cost portion of the DOC can be further subdivided into fuel cost allocated to each functional component, shown in the middle. Note that airframe & systems weight, fuselage drag, and propulsion system losses make up the largest portion of the fuel cost. The propulsion system contribution can be further subdivided according to the various engine components, shown far right. Note that nacelle drag makes the largest contribution to propulsion-related fuel cost, followed by fan losses.

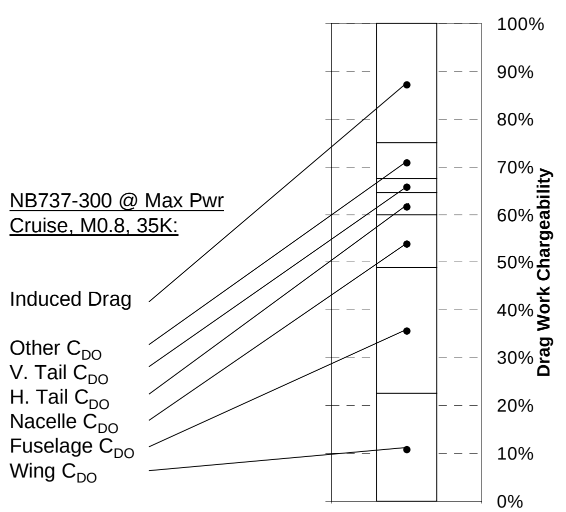

Figure 2: Drag Chargeability for Notional B737 at Cruise Flight Conditions.

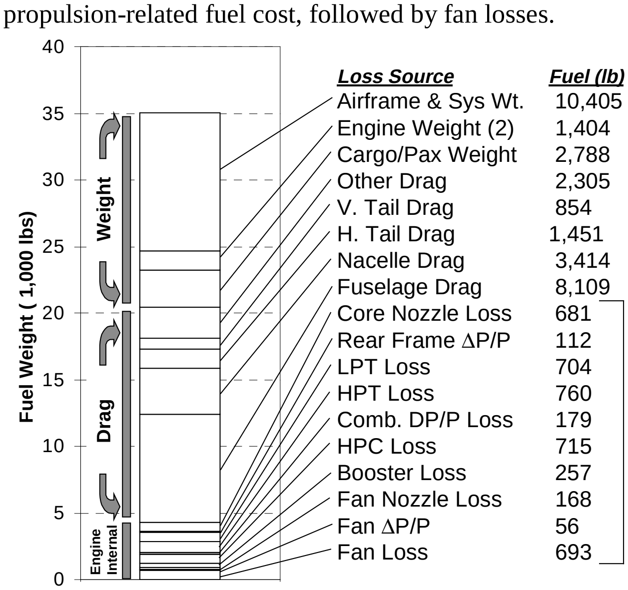

Figure 3: Total Fuel Weight Chargeability for Pure Cruising Flight.

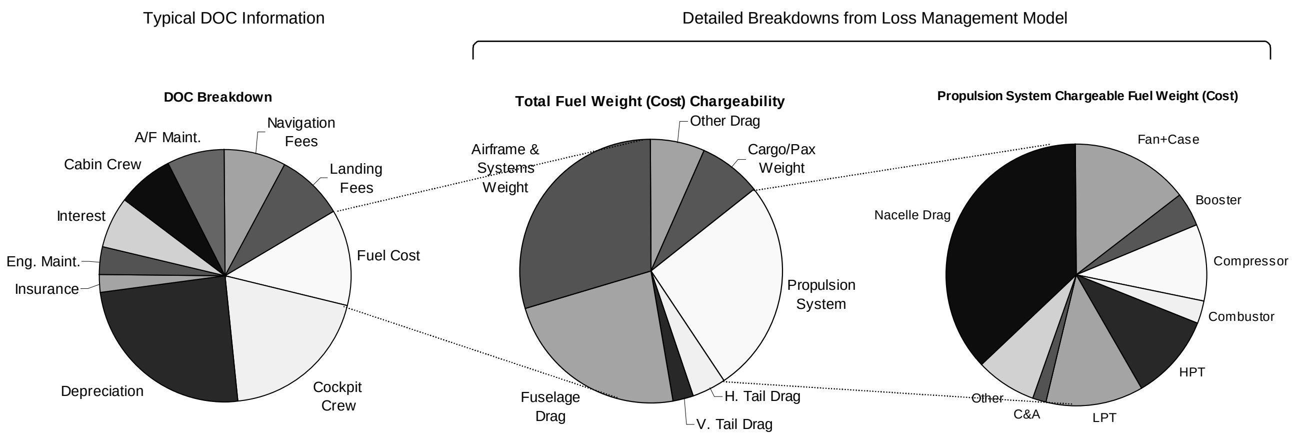

Figure 4: Typical Operating Cost Breakdown (Engine Component Level).

The total propulsion system contribution to vehicle gross weight is summarized in Table III. In effect, this table indicates that 17,745 lb (14%) of the B737-300 ramp weight is *directly chargeable* to the propulsion system. This is a result that cannot be directly estimated with the standard analysis techniques in use today. Moreover, the analysis presented here focuses on the propulsion system, but the method is general and could be applied to obtain detailed weight and cost breakdowns for any system or subsystem of any vehicle (ship, car, etc).

Impact of Environmental Requirements/Technology: One area where loss management models have potential application is in evaluation of the impact due to environmental constraints such as acoustic noise and exhaust emissions on vehicle size, performance, and cost. Since environmental requirements are a relatively new aspect to the aircraft engine industry, there is considerable uncertainty as to the most appropriate way to accommodate these requirements. The use of loss management models to evaluate the impact of environmental technologies and their attendant risk would allow one to systematically evaluate and track *each and every loss* resulting from requirements on emissions and noise. The presence of uncertainty implies that the loss must be expressed as a distribution. Ultimately, this will enable the development of balanced designs that achieve the best compromise between cost and environmental capability. For example, acoustic noise requirements typically drive modern turbofan engines towards higher bypass ratios and larger fans. This results in increased nacelle drag, heavier engines, and higher manufacturing costs. The key is to balance this fuel burn and manufacturing cost penalty against the cost of the environmental impact incurred by alternate (performance-driven) designs. Application of these methods to this problem would allow explicit calculation of the absolute impact as well as all contributing components due to environmental requirements.

Table III : Total Fuel Weight Chargeable to the Propulsion System.

Engine Weight	1,404
Nacelle Drag	3,414
Internal Loss	4,325
Total Fuel	9,143 lb
Engine Weight	8,602
Total Prop. System Contribution:	17,745 lb

Conclusions: The loss management modeling techniques described and applied in this paper represent a physics-based means of evaluating the total cost of each source of loss in any general vehicle. This method allows the evaluation of absolute cost rather than relative cost, and could be a valuable tool in assisting the designer to achieve better balance in vehicle designs by showing how each of the various systems interacts to produce an optimum design. Furthermore, it is valuable as means of showing which functional groups make the largest contributions to gross weight, fuel weight, operating cost, etc. Finally, it is a powerful tool to assist the designer in reconciling conflicting requirements on acoustic noise, emissions, weight, performance, etc. by expressing all these items in terms of a single figure of merit: cost.

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